The mass-metallicity relation of tidal dwarf galaxies

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Received: accepted

ABSTRACT

Dwarf galaxies generally follow a mass-metallicity (MZ) relation, where more massive objects retain a larger fraction of heavy elements. Young tidal dwarf galaxies (TDGs), born in the tidal tails produced by interacting gas-rich galaxies, have been thought to not follow the MZ relation, because they inherit the metallicity of the more massive parent galaxies. We present chemical evolution models to investigate if TDGs that formed at very high redshifts, where the metallicity of their parent galaxy was very low, can produce the observed MZ relation. Assuming that galaxy interactions were more frequent in the denser high-redshift universe, TDGs could constitute an important contribution to the dwarf galaxy population. The survey of chemical evolution models of TDGs presented here captures for the first time an initial mass function (IMF) of stars that is dependent on both the star formation rate and the gas metallicity via the integrated galactic IMF (IGIMF) theory. As TDGs form in the tidal debris of interacting galaxies, the pre-enrichment of the gas, an underlying pre-existing stellar population, infall, and mass dependent outflows are considered. The models of young TDGs that are created in strongly pre-enriched tidal arms with a pre-existing stellar population can explain the measured abundance ratios of observed TDGs. The same chemical evolution models for TDGs, that form out of gas with initially very low metallicity, naturally build up the observed MZ relation. The modelled chemical composition of ancient TDGs is therefore consistent with the observed MZ relation of satellite galaxies.

Key words: Stars: abundances – stars: luminosity function, mass function – supernovae: general – Galaxies: evolution – Galaxies: dwarf – Galaxies: star clusters: general

1 INTRODUCTION

Dark-matter-free tidal dwarf galaxies (TDGs) may constitute an important contribution to the dwarf galaxy population. TDGs are dwarf galaxies that form from the tidal debris of baryonic material liberated from giant galaxies after they interact with other galaxies (see Bournaud 2010 and Duc 2012 for reviews). TDGs do not contain significant amounts of dark matter because it cannot be captured by their weak gravitational potentials (Barnes & Hernquist 1992; Kroupa 1997; Bournaud 2010; Kroupa 2012, Dabringhausen & Kroupa 2013, Kroupa 2015).

It is generally thought that TDGs do not build a mass-metallicity (MZ) relation because their metallicity is

dominated by recycled material coming from the parent (large) interacting galaxies. This is certainly true for recently formed TDGs, for which in-situ production of metals is negligible compared to the metals coming from the interacting galaxies. Indeed, recently formed TDGs are most easily found as MZ outliers (Duc & Mirabel 1994; 1998; Weilbacher et al. 2003; Croxall et al. 2009; but see also Reverte et al. 2007). However, it is commonly argued that the production rate of TDGs was much higher in the past, due to the larger gas fractions and the smaller relative distances between galaxies. Although the fraction of surviving TDGs is unknown (see Kroupa 1997; Okazaki & Taniguchi 2000; Bournaud & Duc 2006; Kaviraj et al. 2012; Dabringhausen & Kroupa 2013 for different and conflicting estimates), numerical simulations show that these galaxies can survive the tidal field of the parent galaxy and the internal feedback processes for many Gyr (Kroupa 1997; Klessen & Kroupa 1998; Recchi et al. 2007; Casas et al. 2012; Ploeckinger et

lass-metallicity (MZ) relation because their metallicity

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al. 2014, 2015). Ancient TDGs are therefore born out of relatively unpolluted material and the subsequent chemical evolution is solely due to internal processes. They have thus the possibility to build a MZ relation as any other galaxy (see also Kroupa 2015).

The aim of this paper is to determine the MZ relation of ancient TDGs (born out of low-metallicity gas) and to compare them with the observations of a sample of dwarf galaxies in the Local Universe. We want to test whether these objects (or a fraction of these objects) might have had a tidal origin, as their internal dynamical properties (Kroupa 1997; Metz & Kroupa 2007) and the distribution of satellite galaxies about their host galaxies in vast thin disks of satellites and their phase-space correlation suggests (Kroupa, Theis & Boily 2005; Pawlowski et al. 2012; Ibata et al. 2013; Hammer et al. 2013; Pawlowski & Kroupa 2014; Yang et al. 2014; Pawlowski et al. 2014; Ibata et al. 2014a, 2014b, 2015). A recent paper (Collins et al. 2015) shows that the metallicity of dwarf galaxies belonging to the rotating disk of satellites surrounding Andromeda is comparable to the metallicity of off-plane satellites. If the on-plane satellites are of tidal origin, one would expect instead large differences. It is our aim to show that the mild difference can be explained if the on-plane dwarf galaxies are TDGs formed during the very early phases of the evolution of Andromeda and thus out of a very mildly polluted interstellar medium. At the same time, models of younger TDGs, born out of polluted gas, will be compared with observed TDGs.

In a companion paper (Recchi & Kroupa 2015, hereafter Paper I) we have shown how to calculate the metallicity (of stars and gas) of model galaxies based on the integrated galactic IMF (IGIMF) theory (Kroupa & Weidner 2003; Kroupa et al. 2013). We have seen that the IGIMF theory naturally produces a mass-metallicity (MZ) relation, as low-mass galaxies have on average steep massive-star IMF slopes and thus the metal production rate is reduced. We have also noticed that a good fit with the observed MZ relation in the stars of local group dwarf galaxies (based on the Lee et al. 2006 data) can be reproduced if one assumes that low-mass galaxies can expel gas and metals through modest galactic winds. Galactic winds are less likely in large galaxies because of the deeper potential wells (Recchi & Hensler 2013).

In this paper we apply the methodologies of Paper I to the study of the MZ relation in TDGs in order to test whether models of old TDG, born out of unpolluted or modetately polluted gas, can build a MZ relation. We will apply the same models to models of younger TDGs, born out of more significantly polluted gas, in order to test whether the metallicity of observationally identified TDGs can be reproduced.

The outline of this paper is as follows. In Sect. 2 we briefly recall the adopted methodology, extensively described in Paper I. In Sect. 3 the results of this investigation are presented. Finally, in Sect. 4 the main results are discussed and some conclusions are drawn.

2 THE METHOD

We work in the framework of the IGIMF theory, according to which dwarf galaxies, characterized by small levels of star formation rates (SFRs), can produce only a small relative number of massive stars and, hence, the galaxy-wide IMF will be biased toward low-mass stars. In particular, we adopt the detailed IGIMF prescriptions of Weidner et al. (2013), which are able to reproduce a large range of observed galactic properties. We neglect the 'axiom vii' of Weidner et al. (2013), namely we do not consider variations in the slope of the mass distribution of star clusters. We have shown in Paper I that this assumption affects negligibly the results of our numerical calculations.

A single high-resolution simulation of the birth and chemo-dynamical evolution of a TDG using hydrodynamical simulations with stellar feedback (Plöckinger et al. 2014, 2015) is computationally very demanding, and a comprehensive survey of many models cannot be performed with available computers. Simplified models, which contain the essential physics, ar therefore unavoidable if a survey of the chemical and stellar-population properties of TDGs is to be made. We assume the so called 'simple model' of chemical evolution: a one-zone model in which ejecta from dying stars instantaneously mix with the surrounding gas. Moreover, the instantaneous recycling approximation is adopted, according to which the lifetime of stars with masses larger than 1 M_{\odot} can be considered negligible. This approximation is good for α -elements, produced on short timescales by massive stars, but it is not good for elements produced on longer timescales by intermediate-mass stars and Type Ia supernovae. An outflow rate, proportional to the SFR and dependent on the initial gaseous mass of the model galaxy is assumed. In particular, it is assumed that low-mass galaxies, due to their shallower potential wells, develop galactic winds and lose freshly produced heavy elements more easily (Marin 2005; Recchi & Hensler 2013). An infall rate, proportional to the star formation rate, is assumed, too. The solution of the simple model in the presence of infall and outflows is:

$$M_g(t) = M_g(0) \exp\left[\left(\Lambda - \lambda - 1\right)s \int_0^t \left[1 - R(\tau)\right] d\tau\right],$$

$$Z(t) = Z_0 + \frac{\int_0^t \left[1 - R(\tau)\right]s \left[\Lambda Z_A + y_Z(\tau)\right]I(\tau)d\tau}{I(t)},$$

$$I(t) = \exp\left[-\int_0^t \left[1 - R(\tau)\right]s \left[\lambda(\gamma - 1) + \Lambda\right]d\tau.\right]$$
(1)

where M_g is the gas mass, Z is the metallicity, R is the fraction of a stellar population not locked into long-living (dark) remnants, $y_{\rm Z}$ represents the ratio between the mass of heavy elements ejected by a stellar generation and the mass locked up in remnants, and γ is the metallicity enhancement factor in the galactic wind (see Matteucci 2001; Recchi et al. 2008; Recchi 2014; Paper I for more details). The SFR ψ is parametrised as $\psi = s \times M_g$ with the star formation efficiency s (i.e. the inverse of the gas-consumption timescale) taken to be equal to 0.3 Gyr⁻¹ (c.f. Pflamm-Altenburg & Kroupa 2009). The outflow rate is set by $\lambda(1-R)\Psi$ and the infall rate is determined with $\Lambda(1-R)\Psi$. As in Paper I, we assume $\Lambda = 0.5$ and a variable λ , according to eq. 17 there. Finally, Z_i is the initial metallicity and Z_A is the metallicity of the infalling gas, which we assume to be equal to the initial metallicity Z_i . Adopting an universal IMF, the quantities R and y_Z are constant and the integrals appearing above can be explicitly calculated. In the case of the IGIMF, R and y_Z depend on the galactic evolution because the SFR and the metallicity affect the IMF, which in turn affects the calculation of these two quantities. The above expression for Z(t) is thus an implicit equation that must be solved iteratively.

The average metallicity Z_* of the stars in a model galaxy is calculated according to the equation

$$Z_* = \frac{\int_0^t Z(t)\psi(t)dt}{\int_0^t \psi(t)dt},\tag{2}$$

where ψ is the SFR. This expression represents thus the mass-weighted average of the metallicities of all the stellar populations ever born in the galaxy (see Pagel 1997).

3 RESULTS

3.1 Starless initial conditions

At variance with Paper I, in which we considered only unpolluted models of galaxies (i.e. we assumed $Z_i = 0$ in Eq. 1), we consider here different levels of pre-enrichment. In particular, in what follows we consider mild pre-enrichments $(Z_i = 10^{-3} \text{ and } 10^{-2} \text{ Z}_{\odot})$ and large pre-enrichments $(Z_i =$ 0.1 and $0.5 Z_{\odot}$). In compliance with the results of Paper I, we consider for the moment starless initial configurations, i.e. we assume that the TDGs form out of the gaseous component of a tidal arm. We will relax this assumption in Sect. 3.3. Notice that the effect of Z_i on the solution is not linear as Eq. 1 might suggest because, according to the adopted IGIMF recipes, a different initial metallicity changes also the initial IMF, and a changing metallicity leads to a changing IGIMF. We wish to consider model solutions applicable to very old but also to young TDGs. We will compare the abundances of very old TDGs with the ones in a sample of dwarf galaxies in the local volume, including dwarf satellites orbiting around the Milky Way and Andromeda.

Notice that the dwarf satellites closest to the Milky Way and Adromeda are usually dwarf Spheroidals or dwarf Ellipticals. For these galaxies, gas-phase abundances, obviously, can not be determined, and one resorts on stellar abundances (usually expressed as [Fe/H], as the iron composition of stars is easy to determine) to estimate the global metallicity of the galaxy. Many observations are available concerning the average [Fe/H] in dwarf satellites and the resulting MZ relation (see e.g. Kirby et al. 2013). In principle, these observations can be compared with our results, obtained by means of Eq. 2. However, in Paper I we showed that the instantaneous recycling approximation can not be applied to iron, which is mainly produced on timescales longer than 50 Myr (Matteucci & Recchi 2001). In paper I we thus compared our results with the sample of Lee et al. (2006). This includes the gas-phase oxygen abundances of many gas-rich dwarf galaxies of the Local Group, as well as other dwarf galaxies of the Local Universe, not belonging to the Local Group. Notice also that, in the case of younger TDGs, more data are available on the gas-phase abundances, therefore we will compare the oxygen gas-phase abundance with available observations in TDGs (taken from Boquien et al. 2010 and Duc et al. 2014). In order to have consistent datasets to compare with our results, and in order to be consistent with

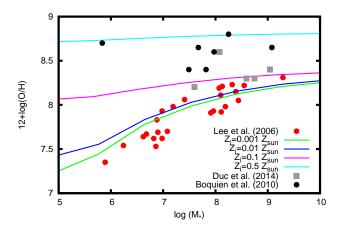


Figure 1. The MZ relation obtained by means of the simple model of chemical evolution within the IGIMF theory, with different values of the initial metallicity Z_i (see Eq. 1). Here, we compare the gas-phase abundance of the model galaxies with observations of dwarf galaxies in the Local Universe (from Lee et al. 2006; red circles) and of young TDGs (from Boquien et al. 2010 - black circles; Duc et al. 2014 - grey squares). Notice that the x-axis indicates the final stellar mass of the model galaxies, although the comparison focuses on gas-phase abundances. Notice also that the lower two curves ($Z_i = 10^{-3}$ and 10^{-2} Z $_{\odot}$) correspond to old TDGs and evolve for a longer time (see text for details).

Paper I, we will consider only the gas-phase oxygen abundances of galaxies, and we will compare the results of models with low pre-enrichments with the observations of Lee et al. (2006), and the ones with high pre-enrichments with the results of Boquien et al. (2010); Duc et al. (2014). We need to consider also different evolutionary times for the evolution of young and old TDGs. We assume therefore an age of 12 Gyr (the same evolutionary time considered in Paper I) for the old TDGs and of 3 Gyr (see Duc et al. 2014) for the younger ones. In particular, we assume here that the models with low pre-enrichment ($Z_i = 10^{-3}$ and 10^{-2} Z_{\odot}) are old TDGs, evolving for 12 Gyr, whereas models with higher pre-enrichment ($Z_i = 0.1$ and 0.5 Z_{\odot}) are younger and evolve for 3 Gyr. The resulting theoretically derived MZ relations are shown in Fig. 1.

We can see from Fig. 1 that the models reproduce very well the observations of Lee et al. (2006) for mild levels of pre-enrichment ($Z_i = 10^{-3}$ or 10^{-2} Z_{\odot}) and that indeed these results do not differ much from the ones with $Z_i = 0$ presented in Paper I. On the other hand, larger values of Z_i (up to $Z_i = 0.5$ Z_{\odot}) are required in order to fit the gas-phase abundances of younger TDGs.

3.2 TDGs versus dark matter dominated dwarf galaxies

Since we have shown that old TDGs do not stand out in a MZ relation as young TDGs do, the question arises on how we can possibly distinguish old TDGs from galaxies of similar sizes and ages but not of tidal origin.

Assuming the gas infall for TDGs originates preferentially from the tidal debris of the same galaxy interaction process, not only the initial pre-enrichment, but also the in-

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fall parameters differ from the DM-dominated dwarf galaxy case. The gaseous material within the tidal arm is naturally close to the TDG in phase-space, and can therefore be captured easily, which could increase the infall rate.

However, in the framework of the simple models of chemical evolution we can not fix the infall rates, we can only fix the ratio between the infall rates and the SFR (the parameter Λ introduced above). This scenario can be properly addressed only by means of more detailed but also computationally very demanding chemo-dynamical simulations, such as pioneered by Ploeckinger et al. (2014, 2015).

In addition to a potentially increased infall rate, the infalling tidal debris is homogeneously pre-enriched $(Z_A = Z_i)$. Tidal tails do not show a steep metallicity gradient as it is typical for unperturbed late-type galaxies (Bresolin et al., 2009). Their metallicity distribution is homogenised along the tidal arm (Kewley et al., 2010), possibly by radial gas mixing during the galactic collision (Rupke et al., 2010). Contrary to that, the infall into DM-dominated dwarf galaxies is assumed to be of primordial abundance $(Z_A = 0)$.

If long-living TDGs form continuously throughout the history of the Universe and therefore with a range of initial metallicities, one could expect that they do not follow a tight MZ-relation but cover a large region in MZ diagram. The results of the chemical evolution model presented in Fig. 1 explain why this is not the case. For low initial metallicities ($< Z_i \approx 0.01\,\mathrm{Z}_\odot$), the theoretical MZ-relations are very similar to each other and the results are almost indistinguishable whether the infall has primordial abundance $Z_A=0$ (Paper I) or the initial metallicity $Z_A=Z_i$ (Fig. 1). Therefore, old TDGs that formed with a range of low initial metallicities fall on the same MZ-relation.

Increasing the metal pre-enrichment of the tidal debris affects both the initial metallicity of the TDG, and the metallicity of the infalling gas. This leads to an accelerated evolution of the MZ-relation for higher initial metallicities. Note the large difference between the models for $Z_i = 0.1 \, \mathrm{Z}_{\odot}$ and $Z_i = 0.5 \, \mathrm{Z}_{\odot}$ already after 3 Gyr (Fig. 1).

This accelerated evolution can therefore explain the gap between the MZ-relation for old TDGs and position of the very young TDGs in the MZ-diagram. Furthermore, if most of the satellite galaxies were born as TDGs at a high red shift, with the production rate of TDGs diminishing with cosmic time due to a decreased galaxy–galaxy encounter rate, then this would enhance the gap even further.

Another difference between TDGs and DM-dominated dwarf galaxies can be their star formation efficiencies, and this effect can be tested with our chemical evolution model. As an example, it is known for a long time that isolated galaxies have lower star formation efficiencies s (i.e. longer gas-consumption time-scales, Pflamm-Altenburg & Kroupa 2009) than interacting galaxies (e.g. Sanders & Mirabel 1985, Solomon & Sage 1988). If s depends on the environment also on dwarf galaxy scales, the star formation efficiencies for DM-dominated dwarf galaxies and TDGs could be different. We can thus analyse what happens to the MZ relation if we use a different star formation efficiency. Fig. 2 shows a comparison for the low pre-enrichment cases between our fiducial model with $s = 0.3 \text{ Gyr}^{-1}$ and chemical evolution models where s is decreased by a factor of 2 (labelled with "low SFE" in Fig. 2). These models attain lower metallicities, mainly due to the lower SFRs (recall that, ac-

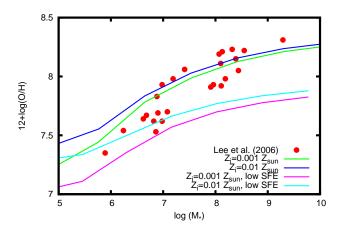


Figure 2. The effect of different star formation efficiencies. The curves $Z_i = 0.001 Z_{\odot}$ and $Z_i = 0.01 Z_{\odot}$ are the same as in Fig. 1. The other two curves have been obtained by halving the star formation efficiency s. As in Fig. 1, red circles correspond to the Lee et al. (2006) sample of galaxies

cording to the IGIMF prescriptions, low SFRs correspond to an lower number of SNeII relative to an IMF description without a truncation at the massive star end).

As seen in Fig. 2, while the low SFE lines match the observations of Lee et al. (2006) for stellar masses below $10^7\,\mathrm{M}_\odot$, the models underestimate the metallicities of systems with higher stellar masses. Detailed observational and numerical studies are required to constrain the star formation efficiency for old dwarf galaxies as well as for young TDGs, to further improve the accuracy of the chemical evolution models.

3.3 Initial conditions made of gas and stars

We now assume that the initial TDG model contains gas and stars, both recycled from the larger interacting galaxies. In particular, we assume that the initial configuration is characterized by an initial stellar mass $M_{*,0}$ which is equal to δ times the initial gaseous mass $M_{g,0}$. These stars might come directly from the parent galaxy, but they might also be the result of a tidally induced burst of star formation. According to the simple model assumptions (see Paper I for a summary), a fraction of these stars die instantaneously and restore $RM_{*,0} = R \delta M_{g,0}$ solar masses of gas into the interstellar medium (ISM). The initial gaseous mass we have to consider in our models is thus $M_{g,0} + R \delta M_{g,0} = M_{g,0}(1 + R\delta)$. This pre-existing stellar population releases also metals into the ISM. The mass in metals at the initial time is given by

$$M_Z(0) = M_{g,0} Z_i + (1 - R) M_{*,0} y_Z.$$
 (3)

The first term represents the contribution due to the gas initially present in the model galaxy, whereas the second term is the amount of heavy elements instantaneously produced by a population of stars with mass $M_{*,0}$. The initial metallicity of our model galaxy is thus:

$$Z(0) = \frac{M_Z(0)}{M_g(0)} = \frac{Z_i + (1 - R) \delta y_Z}{1 + \delta R}.$$
 (4)

For small values of δ , this initial metallicity correctly tends to Z_i , but for larger values of δ , the metallicity produced

by the initially present stars plays a prominent role and the initial metallicity Z(0) is less dependent on Z_i , i.e. the pristine generation of stars injects so many metals into the ISM that the role of the initial gaseous metallicity Z_i becomes negligible. Only the initial SFR remains to be determined, as this SFR determines the initial values of R and y_Z according to the IGIMF prescriptions. We assume for simplicity that this initial SFR is given by $M_{*,0}/9 \,\mathrm{M}_{\odot} \,\mathrm{Gyr}^{-1}$, i.e. it is the SFR required to build $M_{*,0}$ solar masses of stars in 9 Gyr at a constant rate (recall that we are assuming that the TDG models evolve for 3 Gyr thereafter in isolation).

Fig. 3 shows the results of our calculations for $\delta = 0.2$, $\delta = 0.6$ and $\delta = 1.0$. As predicted, the models with $\delta = 0.2$ differ very little compared to the models shown in Fig. 1 (which correspond to $\delta = 0$). The agreement with observations can still be considered satisfactory. For larger values of δ , the various tracks get close to each other. Once again, this is due to the fact that the initial metallicity is set by the instantaneous recycling of metals from the pristine stellar population and Z_i plays a less important role.

4 DISCUSSION AND CONCLUSIONS

Many papers in the recent literature focus on the inconsistencies between the results of cosmological hydrodynamical simulations and the properties of dwarf galaxy satellites of the Milky Way (Klypin et al. 1999; Moore et al. 1999; Kroupa et al. 2005; Kroupa et al. 2010; Boylan-Kolchin et al. 2012 among others; see Kroupa 2012 for a review). In particular, the spatial distribution of satellites orbiting the Milky Way and Andromeda and their phase-space correlations suggest rather strongly that these objects might be of tidal origin (Metz et al. 2007; Pawlowski et al. 2012). Although many other hypotheses have been put forward to explain the spatial distribution of dwarf satellites (e.g. Bahl & Baumgardt 2014), a detailed analysis reveals that their properties and spatial arrangement fail to be accounted for if they were dark-matter-dominated substructures (Ibata et al. 2014b; Pawlowski et al. 2014; Kroupa 2015; Ibata et al. 2015).

If the dwarf satellites of the Milky Way and Andromeda (or a fraction of them) are of tidal origin, one might expect their metallicity to be very large, comparable to the metallicity of the external parts of disks of large spiral galaxies, i.e. a few tenths of Z_{\odot} . Clearly, dwarf satellites of the Milky Way and of Andromeda do not attain such large metallicities. On average, the metallicities are very low, and there is a clear correlation between the stellar mass and the stellar metallicity, although this correlation seems to flatten out at low masses. Indeed, recently formed TDGs, still embedded in the parent tidal arm, have metallicities much larger than their stellar mass would suggest (Duc & Mirabel 1998; Weilbacher et al. 2003), indicative of the fact that they are born out of recycled material, processed by a very large galaxy.

It has been suggested that the dwarf satellites of the Milky Way can have been formed many Gyr ago as TDGs, during the early phases of the evolution of the Milky Way and Andromeda (Kroupa et al. 2005; see also Fouquet et al. 2012; Hammer et al. 2013; Yang et al. 2014; and notably Zhao et al. 2013). In this way, their initial metallicities could have been very low and their initial gas fractions very high.

The subsequent chemical evolution of these objects is no longer directly affected by the parent galaxies (only the tidal field might have played a role) and follows the usual routes of isolated galaxies, i.e. it is mainly affected by astration (the galactic cycle of chemical elements, due to ejection from dying stars and recycling through new generations of stars) and, in the case of very low-mass galaxies, galactic outflows. On the other hand, younger TDGs, born in the last few Gyr, are born out of material with a much higher metallicity, thus "endogenous" processes (star formation, feedback, galactic flows) play a minor role for the chemical evolution.

In this paper we have shown that chemical evolution models can well reproduce the correlation between stellar mass and metallicity of both young TDGs and dwarf galaxies in the Local Group. The framework here is the so-called IGIMF theory (Kroupa et al. 2013), according to which small galaxies, characterized by mild levels of SFR, produce very few massive stars and, hence, the nucleosynthesis of heavy elements is severely limited compared to galaxies with higher masses. According to our models, if the dwarf satellites are of tidal origin, they must have been born out of metal-poor material and they must have evolved for many Gyr. If the levels of pre-enrichment range between 0.01 and $0.001 \, \mathrm{Z}_{\odot}$, then there is a very good fit between model predictions and observations. On the other hand, if the initial metallicity is larger than $0.01 \, \mathrm{Z}_{\odot}$, and if the model galaxy evolves in isolation for 3 Gyr, we are able to reproduce well the observed gas-phase abundances in young TDGs (Boquien et al. 2010; Duc et al. 2014). If we consider initial conditions in which the mass of the stellar component is a large fraction of the total baryonic mass, then in this case, this pre-existing stellar population is able to rise instantaneously the metallicity of the model galaxy and the results are much less dependent on the initial metallicity. The metallicity of the gas of many of the observed real TDGs can therefore also be accounted for as having formed containing a very significant pre-existing captured stellar component from the host galaxy.

An interesting possible implication of this work is also that old TDGs (as suggested by the phase-space correlated satellite galaxies, Kroupa et al. 2005; Pawlowski et al. 2014; Ibata et al. 2013, 2014a, 2014b) and normal or primordial dwarf galaxies cannot be readily distinguished at a fundamental level (Kroupa 2015; Collins et al. 2015). This is one aspect of the failure of the dual dwarf galaxy theorem in a standard dark-matter based cosmological model, with the corresponding possible implications for gravitational physics (Kroupa 2012; 2015).

Implicit in our working hypothesis is the idea that TDGs (or a substantial fraction of them) can survive the tidal torques of the parent interacting galaxies and the internal feedback processes for many Gyr. Although the resilience of TDGs has been shown in our previous numerical investigations (Kroupa 1997; Klessen & Kroupa 1998; Casas et al. 2012; Recchi et al. 2007; Ploeckinger et al. 2014, 2015), long-lasting (more than 3 Gyr) detailed numerical simulations of the chemo-dynamical evolution of initially gas-rich TDGs are required in order to constrain this important problem further.

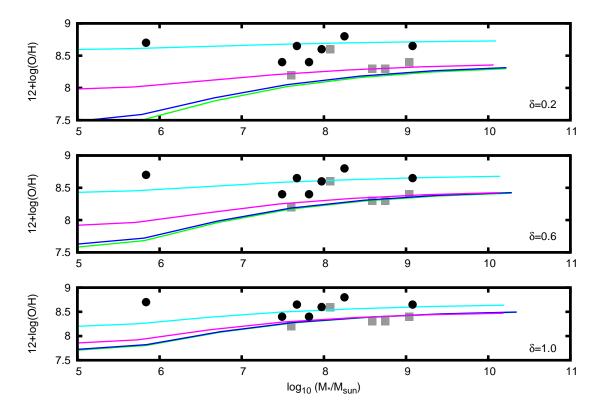


Figure 3. As in Fig. 1, but for initial configurations containing already a population of stars. The parameter δ (indicated in each panel) represents the mass ratio between the initially present stellar component and the gaseous component, i.e. $\delta = \frac{M_{*,0}}{M_{g,0}}$. Color coding and symbols are as in Fig. 1.

ACKNOWLEDGEMENTS

We thank M. Drinkwater for very useful and constructive comments and M. Pawlowski for very useful suggestions. Exchanges of information and ideas with P.A. Duc are also greatly acknowledged. SP acknowledges support from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC Grant agreement 278594-GasAroundGalaxies.

REFERENCES

Bahl, H., & Baumgardt, H. 2014, MNRAS, 438, 2916

Barnes, J. E., & Hernquist, L. 1992, Nature, 360, 715

Boquien, M., Duc, P.-A., Galliano, F., et al. 2010, AJ, 140, 2124 Bournaud, F., 2010, AdAst, 2010, 1

Bournaud, F., & Duc, P.-A. 2006, A&A, 456, 481

Boylan-Kolchin, M., Bullock, J. S., & Kaplinghat, M. 2012, MN-RAS, 422, 1203

Bresolin F., Ryan-Weber E., Kennicutt R. C., Goddard Q., 2009, ApJ, 695, 580

Casas, R. A., Arias, V., Peña Ramírez, K., & Kroupa, P. 2012, MNRAS, 424, 1941

Collins, M. L. M., Martin, N. F., Rich, R. M., et al. 2015, ApJL, 799, LL13

Croxall, K. V., van Zee, L., Lee, H., et al. 2009, ApJ, 705, 723 Dabringhausen, J., & Kroupa, P. 2013, MNRAS, 429, 1858

Duc, P.-A. 2012, Dwarf Galaxies: Keys to Galaxy Formation and Evolution, 305

Duc, P.-A., & Mirabel, I. F. 1994, A&A, 289, 83

Duc, P.-A., & Mirabel, I. F. 1998, A&A, 333, 813

Duc, P.-A., Paudel, S., McDermid, R. M., et al. 2014, MNRAS, 440, 1458

Edmunds, M. G. 1990, MNRAS, 246, 678

Fouquet, S., Hammer, F., Yang, Y., Puech, M., & Flores, H. 2012, MNRAS, 427, 1769

Hammer, F., Yang, Y., Fouquet, S., et al. 2013, MNRAS, 431, 3543

Ibata, R. A., Lewis, G. F., Conn, A. R., et al. 2013, Nature, 493,

Ibata, N. G., Ibata, R. A., Famaey, B., & Lewis, G. F. 2014a, Nature, 511, 563

Ibata, R. A., Ibata, N. G., Lewis, G. F., et al. 2014b, ApJL, 784, LL6

Ibata, R. A., Famaey, B., Lewis, G. F., Ibata, N. G., & Martin, N. 2015, ApJ, in press, arXiv:1411.3718

Kaviraj, S., Darg, D., Lintott, C., Schawinski, K., & Silk, J. 2012, MNRAS, 419, 70

Kewley L. J., Rupke D., Zahid H. J., Geller M. J., Barton E. J., 2010, ApJL, 721, L48

Kirby, E. N., Cohen, J. G., Guhathakurta, P., et al. 2013, ApJ, 779, 102

Klessen, R. S., & Kroupa, P. 1998, ApJ, 498, 143

Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82

Kroupa, P. 2012, PASA, 29, 395

Kroupa, P. 2015, Canadian Journal of Physics, 93, 169

Kroupa, P., Theis, C., & Boily, C. M. 2005, A&A, 431, 517

Kroupa, P., & Weidner, C. 2003, ApJ, 598, 1076

Kroupa, P., Famaey, B., de Boer, K. S., et al. 2010, A&A, 523, AA32

Kroupa, P., Weidner, C., Pflamm-Altenburg, J., et al. 2013, Planets, Stars and Stellar Systems. Volume 5: Galactic Structure

- and Stellar Populations, 115 (astro-ph/1112.3340)
- Lee, H., Skillman, E. D., Cannon, J. M., et al. 2006, ApJ, 647, 970
- Martin, C. L. 2005, ApJ, 621, 227
- Matteucci, F. 2001, The Chemical Evolution of the Galaxy. Astrophysics and Space Science Library (Kluwer Academic Publishers)
- Matteucci, F., & Recchi, S. 2001, ApJ, 558, 351
- Metz, M., & Kroupa, P. 2007, MNRAS, 376, 387
- Metz, M., Kroupa, P., & Jerjen, H. 2007, MNRAS, 374, 1125
- Moore, B., Ghigna, S., Governato, F., et al. 1999, ApJL, 524, L19
- Okazaki, T., & Taniguchi, Y. 2000, ApJ, 543, 149
- Pagel, B. E. J. 1997, Nucleosynthesis and Chemical Evolution of Galaxies, Cambridge University Press
- Pawlowski, M. S., Famaey, B., Jerjen, H., et al. 2014, MNRAS, 442, 2362
- Pawlowski, M. S., & Kroupa, P. 2014, ApJ, 790, 74
- Pawlowski, M. S., Pflamm-Altenburg, J., & Kroupa, P. 2012, MN-RAS, 423, 1109
- Pflamm-Altenburg, J., & Kroupa, P. 2009, ApJ, 706, 516
- Ploeckinger, S., Hensler, G., Recchi, S., Mitchell, N., & Kroupa, P. 2014, MNRAS, 437, 3980
- Ploeckinger, S., Recchi, S., Hensler, G., & Kroupa, P. 2015, MN-RAS, 447, 2512
- Recchi, S. 2014, Advances in Astronomy, 2014
- Recchi, S., & Kroupa, P. 2015, MNRAS, 446, 4168 (Paper I)
- Recchi, S., & Hensler, G. 2013, A&A, 551, A41
- Recchi, S., Spitoni, E., Matteucci, F., & Lanfranchi, G. A. 2008, A&A, 489, 555
- Recchi, S., Theis, C., Kroupa, P., & Hensler, G. 2007, A&A, 470, L5
- Reverte, D., Vílchez, J. M., Hernández-Fernández, J. D., & Iglesias-Páramo, J. 2007, AJ, 133, 705
- Rupke D. S. N., Kewley L. J., Barnes J. E., 2010, ApJL, 710, L156
- Sanders, D. B., Mirabel, I. F. 1985, ApJ, 298, L31
- Solomon, P. M., & Sage, L. J. 1988, ApJ, 334, 613
- Weidner, C., Kroupa, P., Pflamm-Altenburg, J., & Vazdekis, A. 2013, MNRAS, 436, 3309
- Weilbacher, P. M., Duc, P.-A., & Fritze-v. Alvensleben, U. 2003, A&A, 397, 545
- Yang, Y., Hammer, F., Fouquet, S., et al. 2014, MNRAS, 442, 2419
- Zhao, H., Famaey, B., Lüghausen, F., & Kroupa, P. 2013, A&A, 557, L3